Numerical Analysis of Flow Instability in the Water Wall of a Supercritical CFB Boiler with Annular Furnace

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In order to expand the study on flow instability of supercritical circulating fluidized bed (CFB) boiler, a new numerical computational model considering the heat storage of the tube wall metal was presented in this paper. The lumped parameter method was proposed for wall temperature calculation and the single channel model was adopted for the analysis of flow instability. Based on the time-domain method, a new numerical computational program suitable for the analysis of flow instability in the water wall of supercritical CFB boiler with annular furnace was established. To verify the code, calculation results were respectively compared with data of commercial software. According to the comparisons, the new code was proved to be reasonable and accurate for practical engineering application in analysis of flow instability. Based on the new program, the flow instability of supercritical CFB boiler with annular furnace was simulated by time-domain method. When 1.2 times heat load disturbance was applied on the loop, results showed that the inlet flow rate, outlet flow rate and wall temperature fluctuated with time eventually remained at constant values, suggesting that the hydrodynamic flow was stable. The results also showed that in the case of considering the heat storage, the flow in the water wall is easier to return to stable state than without considering heat storage.

Keywords: supercritical CFB with annular furnace; heat storage; flow instability; wall temperature; numerical analysis

Introduction

The combustion technology of circulating fluidized bed (CFB) has the advantages of low NOx emission, wide adaptability, high combustion efficiency and low cost of pollution control, which has been widely used in many fields, such as electric power, petroleum, chemical and waste disposal and so on. Compared with subcritical CFB boiler, the operating parameters and mode of supercritical CFB boiler are high, and the fluid in the tube is likely to operate at the supercritical state of high load, or it may work at the two phase state of lower load. In order to ensure the safe and reliable operation of the equipment, we must ensure that the film boiling(DNB)doesn't occur, and the temperature of tube is in the safe range after the drying up (DRYOUT).

In recent decades, the flow instability has caused wide concern on the design and operation of various heat transfer equipments, such as nuclear reactors, refrigeration plants and boilers. It may result in oscillation of wall temperature, lead to fatigue damage of tube and heat transfer deterioration [1]. Thus making investigations on flow instability is very essential. Since 1938, the domestic and foreign scholars have carried out extensive and

Nomenclature

A	inner cross section area, m^2	z	axial length, m
d_n	inner diameter, m	Δz	space step, m
f	friction factor	**Greek symbols**	

g	gravity, m/s^2	ρ	density, kg/m^3
h	specific enthalpy, J/kg	θ	angle of flow direction with respect to horizontal plane, radian
i	space index	δ_d	dimensional Dirac delta function, m^{-1}
j	time index	α	convective heat transfer coefficient (W/m^2·K)
k	pressure drop coefficient	**Subscripts**	
L	total length of channel, m	*in*	inlet
M	mass flow rate, kg/s	*out*	outlet
n	total number of control volume	*jb*	local
P	pressure, Pa	*n*	inner
ΔP	pressure drop from inlet to outlet, Pa	*f*	fluid
q_l	linear power density, W/m	*w*	wall
F_2	internal surface area per unit length	**Superscripts**	
c_w	specific heat(W/m^2·K)	*0*	the initial steady value
m_w	mass per unit length(kg/m)	*j*	the old time value
t	temperature(℃)	*j*+1	the new time value
Δt	time step, s		

in-depth study on the two-phase flow instability [2-16]. However, there is few research on the problem of the flow instability considering the heat storage of the tube wall metal in a boiler. The heat flux density of the furnace is influenced by the heat storage of metal, then the dynamic characteristics of the furnace will also be influenced, so it is necessary to study the hydrodynamic flow instability of a boiler when the heat storage of the tube wall metal is considered. In this paper, the numerical computational model considering the heat storage of metal and suitable for the analysis of flow instability and the calculation of wall temperature is established by the lumped parameter method. Based on Fortran, the single channel model and the time-domain method are adopted. In order to provide guidance for the design and operation of boiler, we select the loop that is most likely to occur flow instability in the water wall as the research object.

Mathematic model

Generally, there are mainly two kinds of approaches for solving the governing equations of mass, momentum and energy. The first one is frequency-domain method, which converts the linearized equations to transfer functions by Laplace transform [17-23]. However, the frequency domain method can't solve nonlinear problems very well. The second one is time-domain method, based on numerical discretization and integration, which conserves the nonlinear information of the original equations [24-28]. The time domain method is employed in the present code. The temperature of the tube wall can be calculated by using lumped parameter method or distributed parameter method. In this paper, the lumped parameter method is used to analyze and calculate the wall temperature.

Basic assumptions

For the purpose of analyzing the flow instability of boiler, the following assumptions are proposed:

(1) One-dimensional model is employed with considering compressibility and thermal expansion.

(2) The temperature and velocity of water are uniformly distributed in cross section, and water flows only along the axial direction.

(3) Only heat transfer in the radial direction is considered.

(4) Effects of kinetic, potential energy and viscous dissipation on energy equation are ignored.

Transient equations for supercritical fluid

Supercritical water has no phase change which can be regarded as single phase. The basic governing equations of supercritical water are the same as the equations of homogeneous flow model.

The mass equation is:

$$\frac{\partial M}{\partial z} + A\frac{\partial \rho}{\partial t} = 0 \qquad (1)$$

The momentum equation is:

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial z}(\frac{M^2}{\rho A})+A\frac{\partial P}{\partial z}=-\rho gA\sin\theta$$
$$-\left[\frac{f}{d}+K_{in}\delta_d(z)+K_{out}\delta_d(z-L)\right.$$
$$\left.+K_{jb}\delta_d(z-z_{jb})\right]\frac{M^2}{2\rho A} \quad (2)$$

The energy equation is:

$$\frac{\partial(Mh)}{\partial z}+A\frac{\partial(\rho h)}{\partial t}=q_l \quad (3)$$

The state equation is:

$$\rho=f(h,P) \quad (4)$$

The metal heat storage equation is:

$$q_1-q_2=c_w m_w\frac{\partial t_w}{\partial t} \quad (5)$$

The heat transfer equation of working fluid side:

$$q_2=\alpha F_2(t_w-t_f) \quad (6)$$

Numerical calculation method

Discretization

As shown in Fig1, the channel is divided into several control volumes from the inlet to the outlet with equal length of Δz. The non-staggered grid method is used for dividing the control volume of flow channel. The fluid physical state parameters, such as mass flow rate, pressure, density, temperature and enthalpy are located in the center of the control volume. Discretization of the governing equations employs first-order upwind scheme in space phase and implicit scheme in time phase. According to the first-order upwind scheme, physical state parameters on the junction are equal to that of the adjacent upstream control volume. Integration of the governing equations on every control volume yields the following equations:

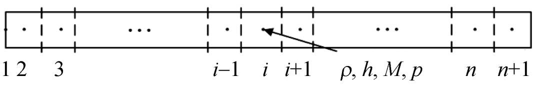

Fig. 1 Schematic diagram of control volume

Mass equation:

$$A\frac{\rho_{i+1}^{j+1}-\rho_{i+1}^{j}}{\Delta t}+\frac{M_{i+1}^{j+1}-M_i^{j+1}}{\Delta z}=0 \quad (7)$$

Momentum equation:

$$\frac{M_i^{j+1}-M_i^j}{\Delta t}+\frac{1}{A\Delta z}\left[\left(\frac{M^2}{\rho}\right)_{i+1}^{j+1}-\left(\frac{M^2}{\rho}\right)_i^{j+1}\right]$$
$$+\frac{A}{\Delta z}\left(P_{i+1}^{j+1}-P_i^{j+1}\right)$$
$$=-\rho_i^{j+1}gA\sin\theta-\frac{1}{2A}\left(\frac{M^2}{\rho}\right)_i^{j+1}$$
$$\left[\frac{f_i^{j+1}}{d_n}+K_{in}\delta_d(z)+K_{out}\delta_d(z-L)\right] \quad (8)$$
$$+K_{jb}\delta_d(z-z_{jb})$$

Energy equation:

$$A\frac{(\rho h)_{i+1}^{j+1}-(\rho h)_{i+1}^{j}}{\Delta t}+\frac{(Mh)_{i+1}^{j+1}-(Mh)_i^{j+1}}{\Delta z}=q_{li}^{j+1} \quad (9)$$

State equation is:

$$\rho_i^{j+1}=f(h_i^{j+1},P_i^{j+1}) \quad (10)$$

The metal heat storage equation is:

$$q_{1i}^{j+1}-q_{2i}^{j+1}=c_{wi}m_{wi}\frac{t_{wi}^{j+1}-t_{wi}^{j}}{\Delta t} \quad (11)$$

The heat transfer equation of working fluid side:

$$q_{2i}^{j+1}=\alpha_i^{j+1}F_{2i}(t_{wi}^{j+1}-t_{fi}^{j+1}) \quad (12)$$

Facilitate the heat transfer equation:

$$q_{2i}^{j+1}\approx\alpha_i^{j}F_{2i}(t_{wi}^{j+1}-t_{fi}^{j}) \quad (13)$$

Boundary conditions

For the single channel model, the boundary conditions are as follows:

(1)inlet enthalpy h_{in} is given and be constant;

(2)inlet pressure P_{in} is given and be constant;

(3)pressure drop from inlet to outlet ΔP is constant.

Solution method

A summary of the solution method is shown in Fig. 2:

(1) The initial values of P, M, h, ρ, t_w, t_f are firstly computed. After that, a small perturbation of heat flux is imposed on the steady state and steps (2)–(5) are repeated to calculate the transient values of the next time step level.

(2) Combine the equation of metal heat storage (11) and heat transfer (13), t_{wi}^{j+1} of the control volume and q_{2i}^{j+1} are solved.

(3) Assume the inlet mass flow rate M_1^{j+1}.

(4) Repeated steps (a) ~ (e) from inlet to outlet, which means i is from 1 to n.

(a) Assume the value of ρ_{i+1}^{j+1}.

(b) According to the mass equation(7) , M_{i+1}^{j+1} is solved.

(c) According to the momentum equation(8) , P_{i+1}^{j+1} is solved.

(d) According to the energy equation(9) , h_{i+1}^{j+1} is solved.

(e) According to the state equation(10) , an improved value of $\rho_{i+1}'^{j+1}$ is obtained by using $P_{i+1}^{j+1}, h_{i+1}^{j+1}$. Compare the density of the former and latter. Repeat steps (b)–(e) until the absolute error of density reaches a desired convergence. $\rho_{i+1}'^{j+1}$ can be treated as an updated guess.

(5) After Step (4), the outlet pressure P_{n+1}^{j+1} is obtained.

If the relative difference $\left|\left(P_{in}-P_{n+1}^{j+1}\right)-\Delta P\right| / \Delta P$ meets the requirement of precision, then the assumption of M_1^{j+1} is correct. Solution turns to next time step level. If not, a chord secant method is used to iterate on M_1^{j+1} until the relative difference is satisfied.

The solution method for steady-state equations is similar to the transient equations which are not mentioned here.

Validation

To validate the present code, calculation results obtained by the present numerical code are compared with the simulation results of Dynastab software. Dynastab software is a kind of commercial software developed by Siemens Ltd for simulating the hydrodynamic flow, aiming at providing guidance for the design and operation of boiler. In this paper, the geometric structure and thermal parameters are the same with those of Dynastab software in practical engineering application of a 600 MW supercritical W-shaped boiler. Initial calculating parameters are shown in Table.1. In order to simulate the flow instability precisely and calculate the wall temperature within a smaller error range, the factors of inclined angle, heat distribution and type of tube are considered, comparison results are shown in Fig.3, Fig.4, Fig.5.

Fig.3 shows that the wave curve of the inlet flow versus time derived from the present program is consistent with the curve derived from Dynastab, it indicates that the method of this paper has certain reliability for simulating the flow instability of the supercritical water.

According to the Fig.4, we can calculate the relative error of the fluid temperature and the wall temperature between program and Dynastab is 0.04% and 0.2%. It proves that the present program is reasonable to simulate the fluid temperature and wall temperature within error limits.

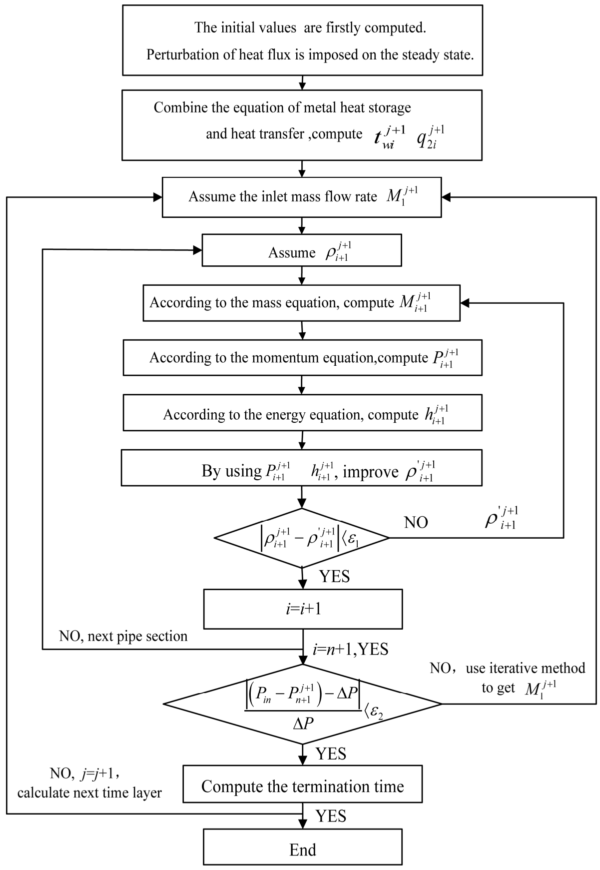

Fig. 2 Program calculation process

Table 1 Initial calculating parameters

Parameter	Value
Inlet pressure	12.566 MPa
Inlet enthalpy	1256.6 kJ/kg
Inlet mass flow rate	0.1367 kg/s
Inlet pressure drop coefficient	0.5
Outlet pressure drop coefficient	1

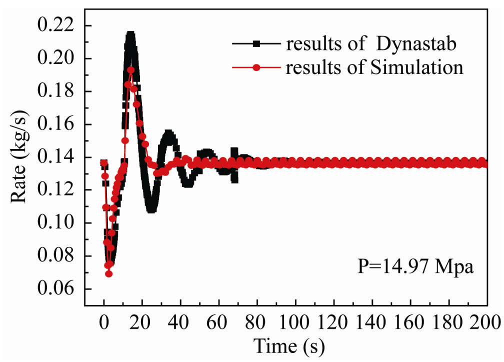

Fig. 3 The inlet flow versus time

Fig.5 shows that the wave curve of the inlet flow versus time in the case of considering heat storage of the tube wall metal is quicker to restore to the initial state

than the flow fluctuation without considering heat storage. It means that the flow in the water wall is more stable with heat storage. This phenomenon indicates that the heat storage of metal is an influence on the dynamic characteristics of the furnace, so it's necessary to consider the heat storage of metal when analyze the flow instability of a boiler.

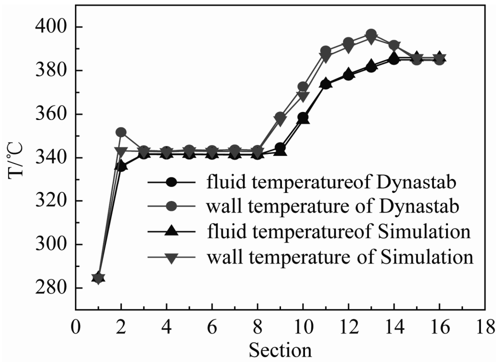

Fig. 4 The outlet temperature distribution of section

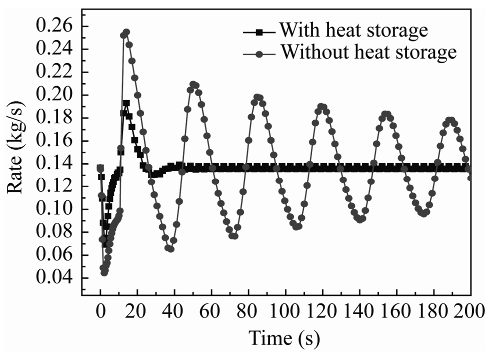

Fig. 5 Effect of heat storage on the inlet flow

Analysis of flow instability in supercritical CFB boiler with annular furnace

Annular furnace

Fig.6 shows the simple structure of the annular furnace. The furnace of boiler is divided into inner and out ring, the outer and inner ring are arranged in parallel. In front wall of the outer ring of furnace, three groups of cyclone separator are set, the same arrangement in back wall. Not only more water cooling walls can be arranged in this structure to obtain enough heat exchange areas, but also this structure reduces the height of furnace and reduces the power consumption of the circulating pump.

In this paper, we selected the sixth loop of the front wall as object of study, the initial calculating parameters are expressed in Table.2. The tube in the loop is vertical smooth tubes with low mass flow, of which the inner and outer diameters are 19mm and 32mm, while the length is 55.6026m.

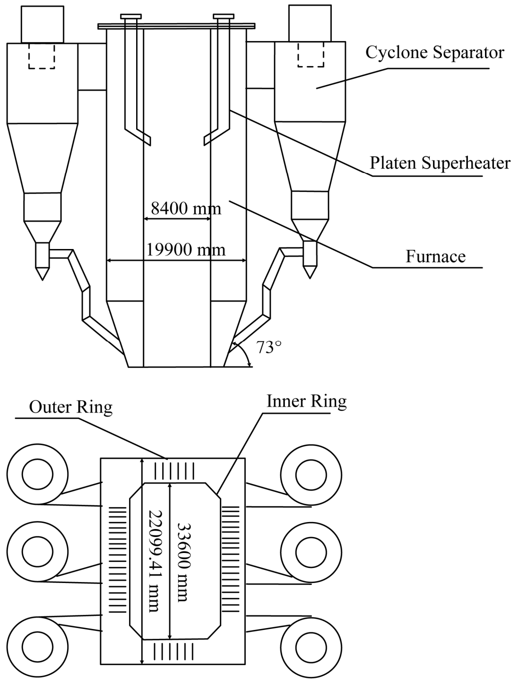

Fig. 6 Structure of annular furnace

Fig.7 and Fig.8 show the pipeline structure and heat load distribution, the distribution of heat load along the height of the furnace is not uniform. According to the characteristics of heat flux distribution along the furnace height, the water wall is divided into more sections where the heat flux experiences a sharp heat flux change and is divided into fewer sections where the heat flux experiences a gentle heat flux change [29]. By doing this, the characteristic of non-uniform distribution of heat flux can be fully considered in calculations. In this paper, the water wall is firstly divided into 33 sections and each section is further divided into equal length which is equivalent to the space step size Δz. Fig. 7 shows the length of each section in which the heat flux is uniformly distributed. Take the space grid length about 0.1m, the loop can be divided into 560 segments, take two constants as the time step Δt to ensure the independence between time and space step. From 0 to 1 s, the time step is 0.1s. From 1 to 500 s, the time step takes 1.0 s.

Table 2 Initial calculating parameters

Parameter	Value
Inlet pressure	10.16 MPa
Inlet enthalpy	1343.1 kJ/kg
Inlet mass flow rate	0.0653 kg/s
Inlet pressure drop coefficient	0
Outlet pressure drop coefficient	0

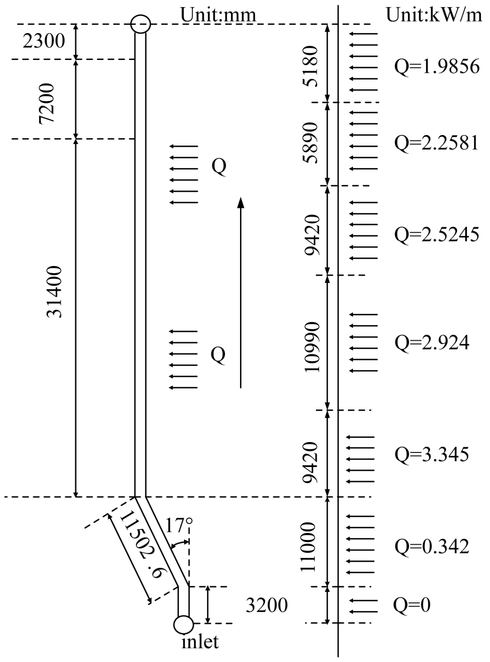

Fig. 7 Geometry of water wall

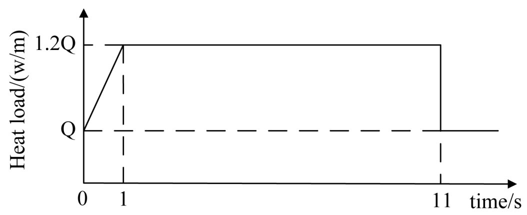

Fig. 8 Heat load distribution versus time

The dynamic characteristics of furnace

The dynamic instability of the furnace occurs when the heat flux density is changed for some reasons. The inlet and outlet of the loop will form a reciprocating cycle mode in which the flow rate increase or decrease when the dynamic instability occurs. If the resistance characteristics of the furnace and the fluctuation of the flow reach a certain resonance, then the flow fluctuations will always be in a stable state of fluctuation and will not decay. In some cases, the temperature of the tube is changed frequently, which leads to fatigue failure of pipe and is not conducive to the safe operation of the boiler, so it should be avoided. In the case of considering heat storage of the tube metal, applying 1.2 times heat load disturbance on the sixth loop, the fluctuation of the inlet flow rate and outlet flow rate versus time is shown in Fig.9.

It can be seen from Fig.9, the inlet flow rate and outlet flow rate versus time were reversed phase fluctuation, when the inlet flow rate increases, the outlet flow rate decreases, when the inlet flow rate decreases, the outlet flow increases, the amplitude of the inlet flow rate and outlet flow rate decreases gradually with time, eventually the outlet flow rate equaled to the inlet flow rate and restore to a steady state, suggesting that the flow condition is stable.

Analysis of the temperature

Without the heat load disturbance, the inlet pressure of the sixth loop at steady state is 10.16 MPa, the inlet enthalpy is 1343.097 kJ/kg and the inlet flow rate is 0.065 kg/s. On the basis of steady state, 1.2 times heat load disturbance is applied on the sixth loop. The simulation results are shown as follows:

Fig.10 shows the average temperature of fluid at steady state and the wall temperature in three cases. At 4.1 s, the heat load reaches the maximum value and the inlet flow rate drops to the minimum value; but at 13.1 s, the inlet flow rate reaches the maximum value and the heat load recoveries to the initial value. In Fig.10, the inflection point of each curve is the phase transition point. Take the steady state as an example, there are two inflection points in the curve of average temperature distribution, one is in the 8th section and the other one is in the 26th section, which means the fluid in the first seven sections is in the single phase liquid state, the fluid which

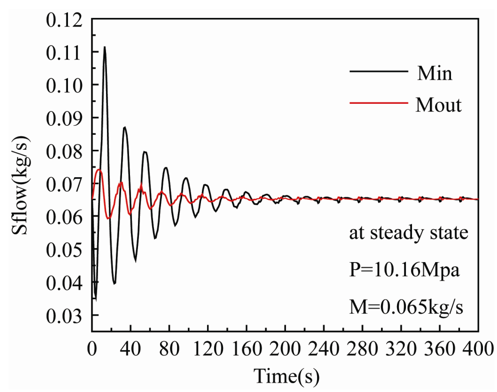

Fig. 9 The flow versus time

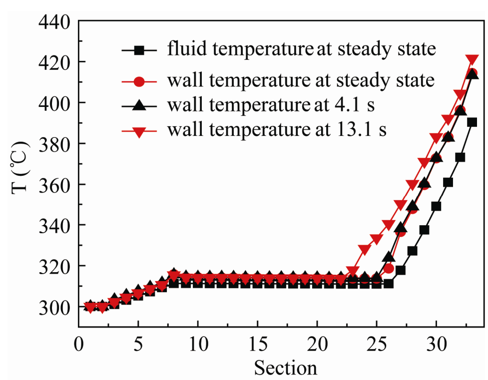

Fig.10 The average temperature of section

is in the section of 8~26th is in the two-phase region, the fluid in the remaining sections is superheated steam. From 1 to 500 s, the maximum temperature of the tube wall is 435℃, which is in the allowable range, so the operation of boiler is safe and reliable.

Fig.11 and Fig.12 exhibit the temperature fluctuation of the 55th control volume (single phase region) and the 275th control volume (two-phase region). From Fig.11 and Fig.12, the fluid temperature and wall temperature fluctuated with time finally remained at constant values. The wall temperature in the single phase liquid zone is only 1.5℃ higher than the fluid temperature, but the value of temperature difference between the wall temperature and the fluid in the two-phase region is 2.8℃.

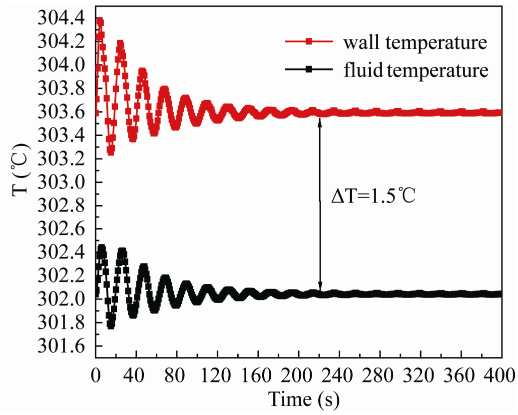

Fig. 11 The temperature of 55th segment versus time

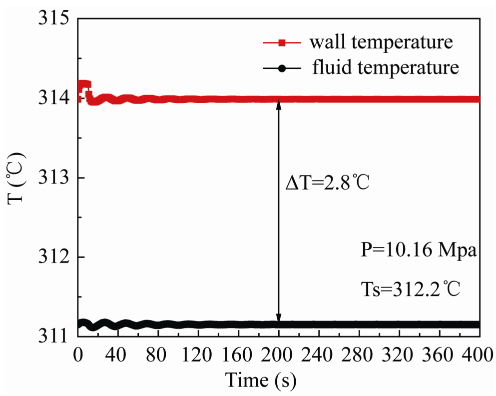

Fig. 12 The temperature of 275th segment versus time

Conclusion

In this study, a general model considering the heat storage of the tube wall metal is proposed. In order to further expand the study of supercritical flow instability of boiler, a numerical program applying time-domain method is developed. The program is capable to simulate the flow instability of boiler with various geometric structures and thermal parameters and calculate the temperature of tube wall. Comparisons with the data of Dynastab numerical calculation show that the present model is suitable and adequate for the analysis of flow instability in water wall and the temperature calculation of the tube wall, so it can be used for practical engineering application.

The numerical analysis of the flow instability in water wall of a supercritical CFB boiler with annular furnace show that applying 1.2 times heat load disturbance on the loop, the inlet flow rate and outlet flow rate versus time were reversed phase fluctuation and eventually the outlet flow rate equaled to the inlet flow rate, the wall temperature fluctuated with time also remained at constant values, suggesting that the flow condition was stable. In addition, the results also showed that in the case of considering the heat storage, the flow in the water wall is easier to return to stable state than without considering heat storage.

Acknowledgments

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